



Nonlinear Photonic Systems for V- and W-Band Antenna Remoting Applications

Sheng-Kwang Hwang
NATIONAL CHENG KUNG UNIVERSITY

10/22/2016
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ IOA
Arlington, Virginia 22203
Air Force Materiel Command

| | | | | | |
|---|--|---|--|---|--|
| REPORT DOCUMENTATION PAGE | | | | Form Approved OMB No. 0704-0188 | |
| <p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services, Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.</p> | | | | | |
| 1. REPORT DATE (DD-MM-YYYY) 23-10-2016 | | 2. REPORT TYPE Final | | 3. DATES COVERED (From - To) 26 May 2015 to 25 May 2016 | |
| 4. TITLE AND SUBTITLE Nonlinear Photonic Systems for V- and W-Band Antenna Remoting Applications | | | | 5a. CONTRACT NUMBER | |
| | | | | 5b. GRANT NUMBER FA2386-15-1-4026 | |
| | | | | 5c. PROGRAM ELEMENT NUMBER 61102F | |
| 6. AUTHOR(S) Sheng-Kwang Hwang | | | | 5d. PROJECT NUMBER | |
| | | | | 5e. TASK NUMBER | |
| | | | | 5f. WORK UNIT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NATIONAL CHENG KUNG UNIVERSITY 1, TA HSUEH RD., TAINAN CITY, 70101 TW | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD UNIT 45002 APO AP 96338-5002 | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR IOA | |
| | | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-JP-TR-2016-0088 | |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT A DISTRIBUTION UNLIMITED: PB Public Release | | | | | |
| 13. SUPPLEMENTARY NOTES | | | | | |
| 14. ABSTRACT <p>Research goal is to generate highly stable and broadly tunable microwaves at V and W bands, that are broadly tunable from 40 GHz to 100 GHz and, at the same time, that are highly stable with a linewidth down to below 1 Hz</p> <p>has been demonstrated using our proposed scheme based on period-one nonlinear dynamics of semiconductor lasers.</p> | | | | | |
| 15. SUBJECT TERMS <p>nonlinear, photonic, antenna, remote, microwave, amplification, bandwidth, modulation</p> | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT SAR | 18. NUMBER OF PAGES 11 | 19a. NAME OF RESPONSIBLE PERSON HONG, SENG |
| a. REPORT Unclassified | b. ABSTRACT Unclassified | c. THIS PAGE Unclassified | | | 19b. TELEPHONE NUMBER (Include area code) 315-229-3519 |

Final Report for AOARD Grant FA2386-15-1-4026

Project Title

Nonlinear Photonic Systems for V- and W-Band Antenna Remoting Applications –
Microwave Generation and Microwave Amplification

Performance Period

May 26, 2015 ~ May 25, 2016

Principal Investigator

Name: Sheng-Kwang Hwang

Position: Professor

Affiliation: National Cheng Kung University

Department of Photonics

Address: 1 University Road, Tainan, 701, Taiwan

Tel: +886-6-2757575 ext. 63922

Email: skhwang@mail.ncku.edu.tw

Abstract

In this project, microwave generation and amplification using period-one nonlinear dynamics of semiconductor lasers for V- and W-band antenna remoting applications have been investigated. For microwave generation, our study indicates that broadly tunable microwave generation from 40 to 100 GHz is feasible. In addition, a stabilization approach based on optical modulation sideband injection locking has been applied to reduce the linewidth down to below 1 Hz for the generated microwaves from 40 to 100 GHz. Compared with other photonic schemes proposed in the literature, such as mode-locked lasers, optoelectronic oscillators, and laser optical heterodyne, our scheme is (1) up to 100 times better in terms of frequency tunability, (2) up to 1000 times better in terms of microwave linewidth and stability, or (3) much simpler in terms of system structure and operation. For microwave amplification, our study shows that power amplification of up to more than 30 dB for microwaves from 40 to 60 GHz is feasible. Microwave amplification for frequencies between 60 and 100 GHz is feasible and, due to the bandwidth limitation of the devices used in our study, remains to be demonstrated experimentally. Compared with other photonic schemes proposed in the literature, such as passive optical filtering and Brillouin scattering, our scheme is (1) more than 100 times better in terms of frequency tunability, (2) more than 100 times better in terms of microwave gain, and (3) much simpler in terms of system structure and operation. These two microwave signal processing

functionalities are either expensive or difficult, if not impossible, to achieve using traditional electronic approaches for V- and W-band applications. Therefore, our proposed photonic schemes provide promising and attractive solutions for various applications at V and W bands in, for example, (1) wireless communication of the 5th-generation or beyond requiring microwaves ranging from 40 GHz to 100 GHz, (2) optical signal processing for optical communications requiring microwaves ranging from 10 GHz to 100 GHz, and (3) phase-array antennas for commercial, academic, and military purposes delivering microwaves through fibers to remote areas for wireless sensing, imaging, and detection.

Introduction

V- and W-band microwaves are of great interest in antenna remoting applications that require long-distance microwave delivery, such as phase-arrayed radars and wireless access networks, since they are capable of providing broader bandwidth for communication, higher resolution for ranging, and better sensitivity for detection. A better solution for such remote delivery is to superimpose the microwaves onto optical carriers and send the optically carried microwaves through optical fibers. Since the intensity of the optical carriers is modulated at the designated microwave frequency, the microwave characteristics can be adjusted optically by manipulating the optical intensity. The capability of processing microwaves using the photonic approach rather than the traditional electronic approach has attracted much attention as it not only provides similar processing functionalities but also improves their performance characteristics. A variety of different photonic schemes and systems have therefore been proposed to carry out various microwave processing functionalities. In this project, we have studied nonlinear dynamics of photonics for V- and W-band microwave generation and amplification. In particular, we have focused on studying period-one nonlinear dynamics in a photonic active device, namely semiconductor laser, for such processing purposes. Some highlights of our research are briefly presented as follows.

Approach

When a semiconductor laser is subject to continuous-wave optical injection, as shown in Fig. 1, different nonlinear dynamical states could be excited, including period-one dynamics and deterministic chaos [15-18]. When a period-one dynamical state is excited, as Fig. 2(a) presents, a regeneration of the optical injection appears. In addition, oscillation sidebands sharply emerge, which are equally separated from the regeneration by an oscillation frequency within the microwave band. The beating of these spectral components at a photodiode therefore generates a microwave signal at the oscillation frequency, as shown in Fig. 2(a). Naturally, such a laser system at the period-one dynamics is a photonic microwave oscillator, which only requires a typical semiconductor laser. The oscillation frequency can be easily adjusted from a few GHz to tens or even hundreds of

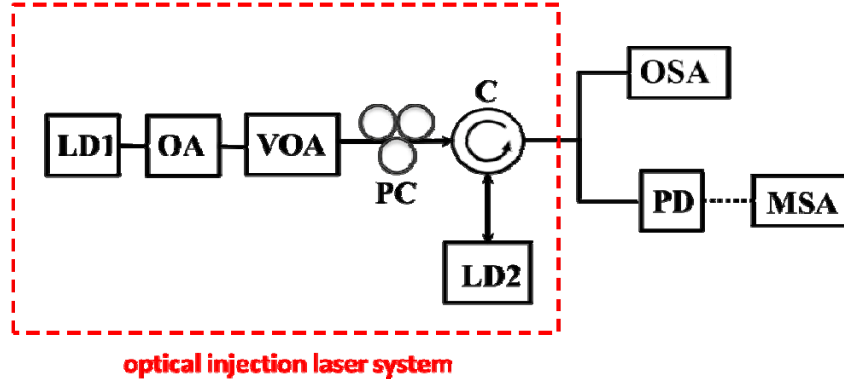


Figure 1: Schematic of the proposed nonlinear photonic system. LD1, laser diode #1; LD2, laser diode #2; OA, optical amplifier; VOA, variable optical attenuator; PC, polarization controller; C, circulator; OSA, optical spectrum analyzer; PD, photodiode; MSA, microwave spectrum analyzer.

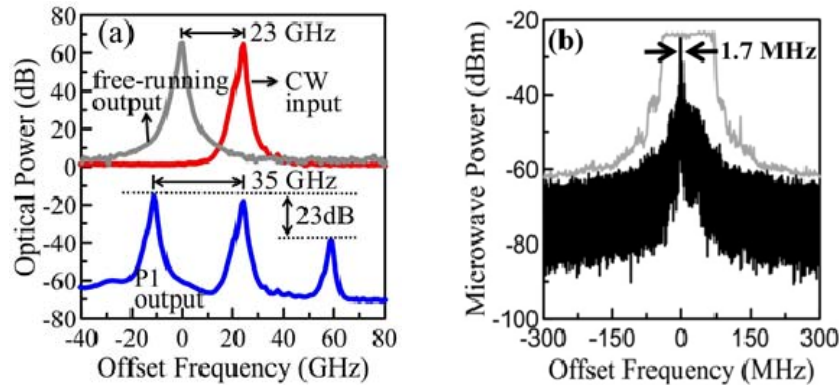


Figure 2: (a) Optical spectra of the system output at free-running (gray curve) and P1 dynamics (blue curve), and of the input optical signal (red curve). For clear visibility, the blue curve is down-shifted with respect to the other curves. The x-axis is relative to the free-running frequency of the injected laser. (b) Microwave spectra of the system output at P1 dynamics (black curve). The trace of the microwave frequency jitters (gray curve) is also shown for an observation period of 100 seconds. The microwave spectrum centers at 35 GHz with a resolution bandwidth of 1 MHz.

GHz by changing the power and frequency of the optical injection. Hence, in this study, we have taken advantage of the period-one dynamics for V- and W-band microwave generation, a photonic yet all-optical scheme. Due to the laser intrinsic noise, however, the linewidth of the generated microwaves is on the order of 1 MHz to 10 MHz, as shown in Fig. 2(b). This poor spectral purity is disadvantageous for practical applications. In this study, we have applied a microwave stabilization approach, the so-called optical modulation sideband injection locking, that nicely works for the microwave generation scheme based on period-one dynamics to greatly reduce the microwave linewidth down to below 1 Hz for V- and W-band microwave generation. Since the optical injection reduces

the necessary gain for the injected laser, the laser cavity resonance red-shifts through the antiguidance effect. As shown in Fig. 2(a), the lower oscillation sideband is therefore resonantly enhanced as opposed to the upper one. As a result, the lower oscillation sideband is not only considerably stronger than the upper one, but also has a power close to the regeneration. Hence, in this study, we have taken advantage of the resonant enhancement of the lower oscillation sideband to increase the optical modulation depth of microwave-modulated optical signals, which in turn results in power amplification of the optically carried microwaves.

Results and Achievements

1. Photonic microwave generation:

Goals: To generate highly stable and broadly tunable microwaves at V and W bands.

Results: Microwave generation that are broadly tunable from 40 GHz to 100 GHz and, at the same time, that are highly stable with a linewidth down to below 1 Hz has been demonstrated using our proposed scheme based on period-one nonlinear dynamics of semiconductor lasers.

Areas of interest:

- (1) broadband (a few to hundreds of Gbit/s) wireless access for commercial and military communication networks, such as the 5th or 6th generation of cellular phone communication networks, which requires microwave carriers ranging from 40 GHz to 100 GHz.
- (2) High-speed optical signal processing for optical communication systems, such as optical clock recovery and division, which requires optical signals carrying microwaves ranging from 10 GHz up to 100 GHz, depending on different system requirements.
- (3) Radar and phase-array antenna for commercial, academic, and military purposes, which use optical carriers to deliver microwave signals to remote areas for wireless sensing, imaging, and detection.

Comparisons with other proposed schemes:

- (1) Mode-locked semiconductor laser:

This scheme generates microwaves that are tunable only within a few gigahertz and that are stable with a linewidth down to the order of 100 Hz to 1 kHz only. Therefore, our proposed scheme is 10 to 100 times better in terms of frequency tunability, and is 100 to 1000 times better in terms of microwave linewidth and stability.

(2) Optical heterodyne:

This scheme generates microwaves with features similar to our proposed scheme. However, many strict and challenging operating conditions are required to satisfy using this scheme in order to yield such microwaves, making it complex and difficult to operate and to achieve the purpose.

(3) Optoelectronic oscillator:

This scheme generates microwaves that are tunable only within a few gigahertz and that are stable with a linewidth down to 1 Hz and even sub-Hz. Therefore, our proposed scheme is 10 to 100 times better in terms of frequency tunability, and is similar in terms of microwave linewidth and stability.

2. *Photonic microwave amplification:*

Goals: To achieve microwave amplification over a broad frequency range at V and W bands.

Results: Microwave amplification for frequency from 40 GHz to 60 GHz and for gain from 10 dB to 30 dB has been demonstrated using our proposed scheme based on period-one nonlinear dynamics of semiconductor lasers. At the moment, the highest demonstrable frequency is limited by the bandwidth of the devices used in our study, not by our proposed scheme. Microwave amplification for frequencies between 60 and 100 GHz is feasible and remains to be demonstrated experimentally.

Areas of interest:

- (1) broadband (a few to hundreds of Gbit/s) wireless access for commercial and military communication networks, such as the 5th or 6th generation of cellular phone communication networks, which requires microwave carriers ranging from 40 GHz to 100 GHz.
- (2) Radar and phase-array antenna for commercial, academic, and military purposes, which use optical carriers to deliver microwave signals to remote areas for wireless sensing, imaging, and detection.

Comparisons with other proposed schemes:

(1) Passive optical filtering:

This scheme is basically not frequency-tunable and gain-tunable unless an optical filter of a different center frequency or of a different pass-band is used. In addition, the highest demonstrable gain is only about 9 dB. Therefore, our proposed scheme is a lot better (you can say 100 times better or more) in terms

of frequency tunability, and is more than 100 times better in terms of microwave gain.

(2) Brillouin scattering:

This scheme is basically not frequency-tunable and gain-tunable. In addition, the highest demonstrable gain is only about 13 dB. Therefore, our proposed scheme is a lot better (you can say 100 times better or more) in terms of frequency tunability, and is more than 100 times better in terms of microwave gain.

These two microwave signal functionalities are either expensive or difficult, if not impossible, to achieve using traditional electronic approaches for V- and W-band applications. Therefore, our proposed photonic approaches provide promising solutions. The results of our research have been presented in **7 conferences (14 contributed papers)**. Moreover, due to our achievements in the study of nonlinear laser dynamics, we have been invited to deliver **4 invited talks at 4 conferences**. In addition, **2 papers have been published in *Optics Express* and 3 papers in preparation**. A list of publications, awards, grants & projects, and academic services over the past year is presented as follows.

I. Publications

Refereed Journal Papers

1. Y.H. Hung and **S.K. Hwang**, “Photonic microwave stabilization for period-one nonlinear dynamics of semiconductor lasers using optical modulation sideband injection locking”, *Optics Express*, Vol. 23, No. 5, pp. 6520-6532 (2015).
2. K.L. Hsieh, Y.H. Hung, **S.K. Hwang**, and C.C. Lin, “Radio-over-fiber DSB-to-SSB conversion using semiconductor lasers at stable locking dynamics”, *Optics Express*, Vol. 24, No. 9, pp. 9854-9868 (2016).
3. K.L. Hsieh and **S.K. Hwang**, “Radio-over-fiber microwave amplification using semiconductor lasers at stable locking dynamics”, in preparation (2016).
4. K.L. Hsieh, C.L. Yang, and **S.K. Hwang**, “Photonic microwave time delay using nonlinear dynamics of semiconductor lasers”, in preparation (2016).
5. Y.H. Hung and **S.K. Hwang**, “Photonic microwave mixing using period-one nonlinear dynamics of semiconductor lasers”, in preparation (2016).

Refereed Conference Papers

Invited Talks

1. Y.H. Hung and **S.K. Hwang**, “Period-one nonlinear dynamics of semiconductor lasers for photonic microwave mixing”, *Proceedings of International Symposium on Nonlinear Theory and Its Applications 2016* (2016) (**Invited Talk**)
2. **S.K. Hwang** and Y.H. Hung, “Tunable and stable generation of millimeter waves

using optically injected semiconductor lasers”, *Proceedings of 2015 Taiwan Terahertz Workshop* (2015) (**Invited Talk**).

3. **S.K. Hwang** and Y.H. Hung, “Highly stable and broadly tunable photonic microwave generation using period-one nonlinear dynamics of semiconductor lasers”, *Proceedings of International Symposium on Nonlinear Theory and Its Applications 2015* (2015) (**Invited Talk**).
4. **S.K. Hwang**, Y.H. Hung, and K.H. Lo, and S. Donati, “High-level dynamics in semiconductor lasers: regimes and applications”, *Proceedings of Numerical Simulation of Optoelectronic Devices 2015* (2015). (**Invited Talk**).

Contributed Talks

1. K.L. Hsieh and **S.K. Hwang**, “Photonic microwave time delays using nonlinear dynamics of semiconductor lasers for antenna remoting applications”, *Proceedings of Optics and Photonics Taiwan, International Conference 2016 (OPTIC)* (2016).
2. K.H. Lo and **S.K. Hwang**, “Photonic microwave generation using optically injected semiconductor lasers subject to short optical feedback”, *Proceedings of IEEE Photonics Conference 2016 (IPC)* (2016).
3. K.L. Hsieh and **S.K. Hwang**, “Photonic microwave time delays using nonlinear dynamics of semiconductor lasers for antenna remoting applications”, *Proceedings of IEEE Photonics Conference 2016 (IPC)* (2016).
4. Y.H. Hung and **S.K. Hwang**, “Semiconductor lasers at period-one nonlinear dynamics for photonic microwave mixing in radio-over-fiber links”, *Proceedings of International Symposium on Physics and Applications of Laser Dynamics 2016 (IS-PALD)* (2016).
5. K.H. Lo and **S.K. Hwang**, “Photonic microwave generation using optically injected semiconductor lasers subject to optical feedback”, *Proceedings of International Symposium on Physics and Applications of Laser Dynamics 2016 (IS-PALD)* (2016).
6. K.L. Hsieh and **S.K. Hwang**, “Nonlinear dynamics of semiconductor lasers for photonic microwave time delays”, *Proceedings of International Symposium on Physics and Applications of Laser Dynamics 2016 (IS-PALD)* (2016).
7. Y.H. Hung and **S.K. Hwang**, “Highly efficient local-oscillator-free photonic microwave down-converters based on period-one nonlinear dynamics of semiconductor lasers”, *Proceedings of the International Society for Optical Engineering (SPIE)*, Vol. 9747, pp. 974718-1-6 (2016).
8. Y.H. Hung and **S.K. Hwang**, “Conversion from non-orthogonal to orthogonal optical single-sideband modulation using optically injected semiconductor lasers”, *Proceedings of 2015 International Topical Meeting on Microwave Photonics (MWP)* (2015).
9. Y.H. Hung and **S.K. Hwang**, “Tunable narrow-linewidth photonic microwave

- oscillators using optically injected semiconductor lasers at period-one dynamics”, *Proceedings of Progress in Electromagnetics Research Symposium 2015 (PIERS)* (2015).
10. K.H. Lo and **S.K. Hwang**, “Photonic microwave generation and stabilization using semiconductor lasers at period-one dynamics”, *Proceedings of Progress in Electromagnetics Research Symposium 2015 (PIERS)* (2015).
 11. K.L. Hsieh and **S.K. Hwang**, “Photonic microwave amplification for radio-over-fiber links utilizing semiconductor lasers at stable locking dynamics”, *Proceedings of Progress in Electromagnetics Research Symposium 2015 (PIERS)* (2015).
 12. Y.H. Hung and **S.K. Hwang**, “Tunable Narrow-Linewidth Photonic Microwave Oscillators Using Optically Injected Semiconductor Lasers at Period-One Dynamics”, *Proceedings of Annual Meeting of the Physical Society of Republic of China* (2015).
 13. K.H. Lo, **S.K. Hwang** and S. Donati, “Optical feedback stabilization of photonic microwave generation using period-one nonlinear dynamics of semiconductor lasers”, *Proceedings of Annual Meeting of the Physical Society of Republic of China* (2015).
 14. K.L. Hsieh and **S.K. Hwang**, “Stable locking dynamics of semiconductor lasers for photonic microwave amplification”, *Proceedings of Annual Meeting of the Physical Society of Republic of China* (2015).

II. Awards

1. Award Title: Best Ph.D. Dissertation Award
 Event & Date: Taiwan Institute of Electrical and Electronic Engineering, Taiwan, 2016.
 Award Winner: Yu-Han Hung
 Dissertation Advisor: **Sheng-Kwang Hwang**
 Dissertation Title: Nonlinear period-one dynamics of optically injected semiconductor lasers for optical signal processing in radio-over-fiber links
2. Award Title: Best Student Paper Award
 Event & Date: 2016 International Society for Optical Engineering (SPIE) Photonics West Meeting, San Francisco, USA, February 13-18, 2016.
 Award Winner: Yu-Han Hung
 Paper Advisor: **Sheng-Kwang Hwang**
 Paper Title: Highly efficient local-oscillator-free photonic microwave down-converters based on period-one nonlinear dynamics of semiconductor lasers
3. Award Title: Best Student Paper Award

Event & Date: 2016 International Symposium on Physics and Applications of Laser Dynamics, Hsinchu, Taiwan, September 7-9, 2016.

Award Winner: Kun-Lin Hsieh

Paper Advisor: **Sheng-Kwang Hwang**

Paper Title: Nonlinear dynamics of semiconductor lasers for photonic microwave time delays

4. Award Title: Best Student Paper Award

Event & Date: 2015 Optics and Photonics Taiwan, International Conference, Hsinchu, Taiwan, December 4-6, 2015.

Award Winner: Yu-Han Hung

Paper Advisor: **Sheng-Kwang Hwang**

Paper Title: Semiconductor lasers at period-one dynamics for local-oscillator-free photonic microwave down-converters

III. Grants & Projects

1. Project Title: Study of exotic nonlinear dynamics using photonicallly perturbed semiconductor lasers

Funding Agent: Ministry of Science and Technology, Taiwan

Contract No.: MOST 103-2112-M-006-013-MY3

Fund: NT\$ 4,481,000

2. Project Title: Photonic scheme and system for ultra-high frequency and ultra-narrow linewidth microwave generation

Funding Agent: Ministry of Science and Technology, Taiwan

Contract No.: MOST 104-2622-E-006-036 -CC2

Fund: NT\$ 1,262,000

3. Project Title: Nonlinear Photonic Systems for V- and W-Band Antenna Remoting Applications – Microwave Generation and Microwave Amplification

Funding Agent: Asian Office of Aerospace Research and Development, U.S. Air Force

Grant No.: FA2386-15-1-4026

Fund: US\$ 25,000